National Aeronautics and Space Administration

Space Technology Mission Directorate
Game Changing Development Program

John Fikes | FY18 Annual Review Presentation | 09.25.2018

Rapid Analysis and Manufacturing Propulsion Technology (RAMPT)

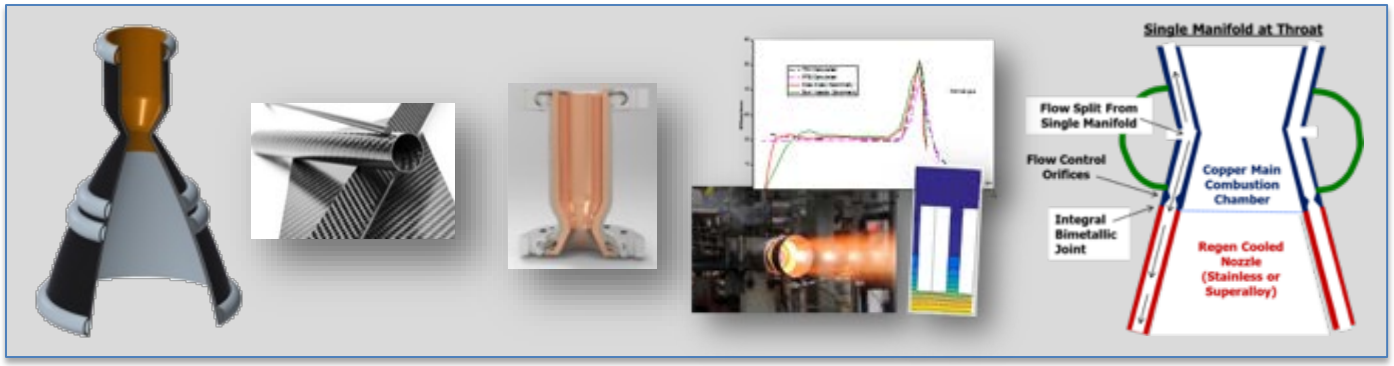
Technology Overview

➢ Technology Product Capability

- The RAMPT project will develop and advance large scale light-weight multi-metallic freeform manufacturing and composite overwrap techniques and analysis capabilities required to implement them to reduce design and fabrication cycles for regeneratively-cooled liquid rocket engine components.
- RAMPT will reduce design, fabrication, assembly schedules while allowing for reduced parts, increased reliability, significant weight reduction and a healthy American supply chain.
- Four technology areas developed: 1) Freeform Blown Powder Nozzle; 2) Composite overwrap structural jacket; 3) Bimetallic radial deposition for manifolds; 4) Modeling and analysis tools for Additive and Regen design

➢ Exploration & Science Impact

- Addresses longest lead, highest cost and heaviest component in engine.
- Applicable to Lunar Lander Engine, Booster Engines, Upper Stage Engines, and NTP Technology.
- Public-private partnerships with specialty industry vendors, government partners, Commercial Crew, and infusion into commercial space companies and manufacturers.
- SSTIP Core Investment Area
  - Launch Propulsion Systems (TA 01)
  - Lightweight Space Structures and Materials (TA12)
  - Manufacturing (TA12)



RAMPT Technology Overview
Key Technologies

Bimetallic Deposited Manifolds
Vendor Development and Optimization

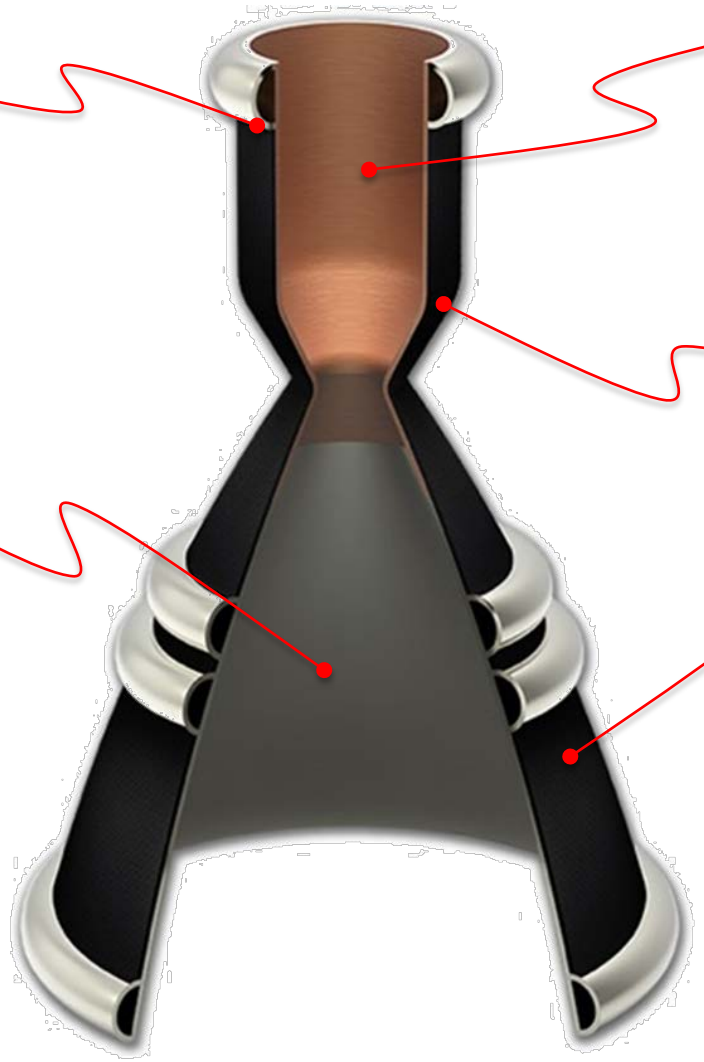
- Develops commercial supply chain
- Reduces Cost
- Optimizes weight based on selective material deposition

Integrated Large Scale Freeform
Manufacturing Deposition Regen-Cooled Nozzle

- Rapid Fabrication for Increased Scale
- Reduces cost and schedule (50%)
- Removes all joints
- Increases reliability
- Reduces complexity

Design and Process Modeling Tools Enable an Integrated Optimized Design

- Reduces design cycles by 60%



3D printed Copper Chamber (derived from LCUSP Program)

- Proven Technology
- Advances Commercial Supply Chain

Composite Overwrap
Thrust Chamber Assembly

- Reduces overall cost and schedule
- Increased performance
- Builds upon COPV Technology

Demonstrate Subscale and Large Scale Hot Fire testing of Multi-material Chamber

- Allows for infusion and increases TRL

Industry Involvement in Key Technologies through Public-Private Partnerships

Mission Infusion & Partnerships

- Infusion/transition plan
  - NASA Projects (SLS, Landers, NTP, Gateway)
  - RAMPT impacts all phases of the engine Thrust Chamber Assembly (TCA) life cycle by reducing design, fabrication, and assembly schedules; allowing for reduced parts, increased reliability, weight reduction and developing a healthy American supply chain.
  - Public-private partnerships with specialty industry vendors, government partners, Commercial Crew, and infusion into commercial space companies and manufacturers.
- Contributing partners and/or stakeholders
  - Public-private partnerships with Auburn University and specialty industry vendors developed under RAMPT project contract.
  - Synergy with SLS Engine Office.

RAMPT Technology Goals & Project Objectives

Technology Goals	
Goal #1	Develop additive and advanced manufacturing methods and design processes that enable new regeneratively-cooled thrust chamber assembly technology.
Goal #2	Identify and optimize additive manufacturing design and fabrication processes that lead to reduced production lead times and analysis life cycle for large scale thrust chamber assemblies.
Goal #3	Engage manufacturing community organizations in the development effort and facilitate infusion of technology into the commercial industry.

Project Objectives	
Objective 1	Freeform deposition additive manufacturing techniques to fabricate an integrated regen-cooled channel wall nozzle structure.
Objective 2	Composite overwrap techniques to significantly reduce weight and provide structural capability for a large Thrust Chamber Assembly (TCA).
Objective 3	Bimetallic and Multi-metallic additive manufacturing and deposition techniques, including copper-alloy to superalloy transitions to optimize material performance.
Objective 4	Advance modeling and simulations of large-scale deposition techniques to obtain optimal property predictions, material designs, and develop “smart” tool-paths to reduce distortion and provide acceptable components.
Objective 5	Develop an integrated regen-cooled combustion chamber and nozzle design tool to significantly reduce design cycles and take full advantage of additive technologies.

RAMPT Performance

Key Performance Parameters				
Performance Parameter	**State of the Art**	**Threshold Value**	**Project Goal**	**Estimated Current Value**
Composite Overwrap Weight (%)	Nickel alloy clad	<75	<50	
Freeform Deposition Strength/Weight (%) [1]	Bolt or welded flanges	>50	100	
Bimetallic Deposition Thrust Class (lbf) [2]	Inco 625 to Copper.	>1200	25,000	
Design Cycle Time (%)	100	<75	<60	

Notes:

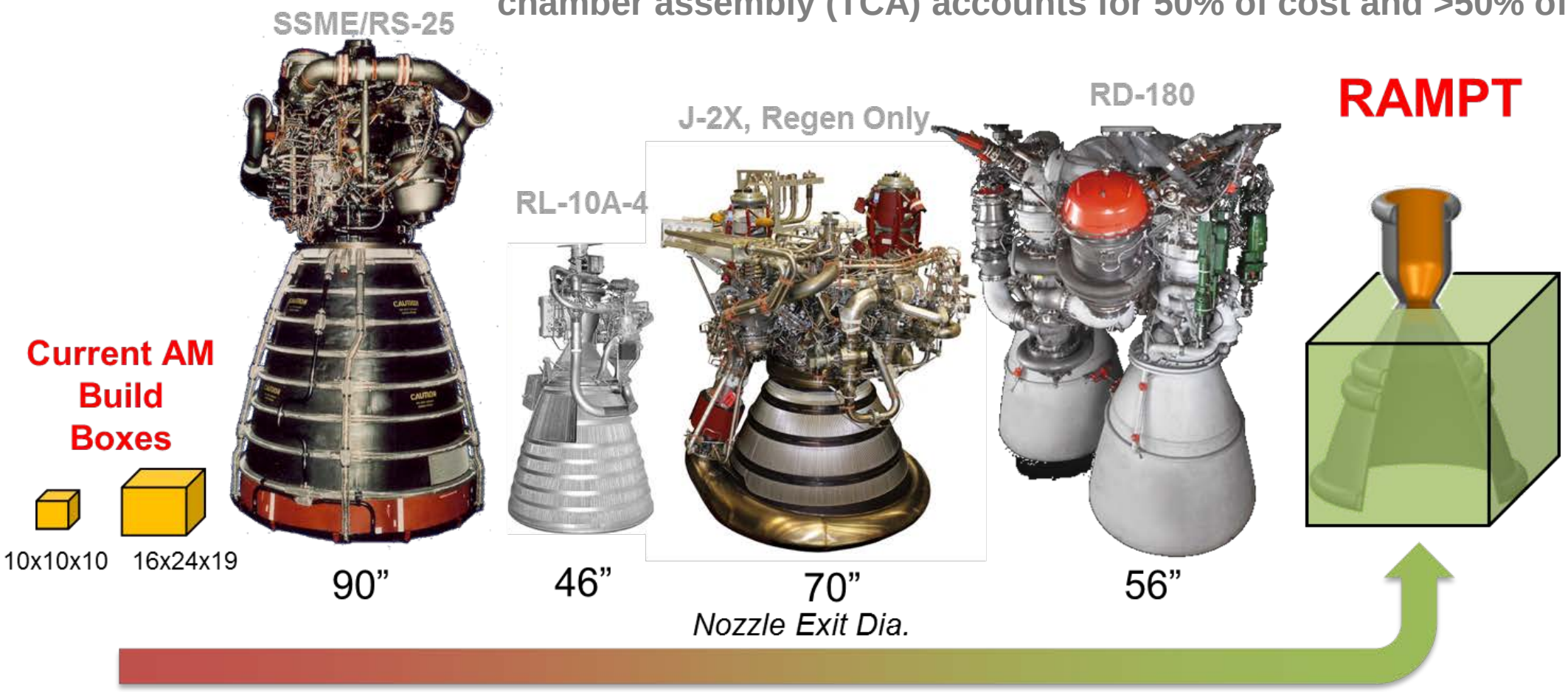
1) Hybrid deposition of integrally built axial joint chamber technology
2) Demonstrate bi-metallic have mechanical properties sufficient for thrust class representative geometry
3) Validate analysis capabilities with empirical data hot fire test campaign

RAMPT Technical Approach

- Plan to accomplish project objectives:
  - Develop and validate significantly reduced mass thrust chamber assembly (TCA) technology using integrated multi-material manufacturing techniques and demonstrate through hot-fire testing.
  - Develop, characterize, and integrate manufacturing and design processes relative to regeneratively-cooled thrust chamber assembly including:
    1. Freeform laser deposition technology to fabricate large-scale regeneratively-cooled nozzle components >3 feet diameter.
    2. Composite overwrap jacket for thrust chamber assembly providing significant weight reduction.
    3. Bimetallic radial deposition to optimize materials for coolant distribution manifolds.
    4. Significant schedule reduction in design, analysis and fabrication cycle through development of design and analysis tools optimized for additive manufacturing thrust chamber assembly design.
  - Complete process development and subscale testing to obtain early manufacturing process evaluations of concepts.
  - Focus manufacturing process and material characterization development leading towards scale up of the integrated thrust chamber assembly.
  - Complete large-scale manufacturing of the integrated thrust chamber assembly hardware.
  - Perform full scale hot-fire testing of TCA.
  - Partner through public-private partnerships with commercial companies to complete manufacturing process developments to enable a long-term supply chain available to government and commercial rocket industry.

Current State of industry and Size Constraints

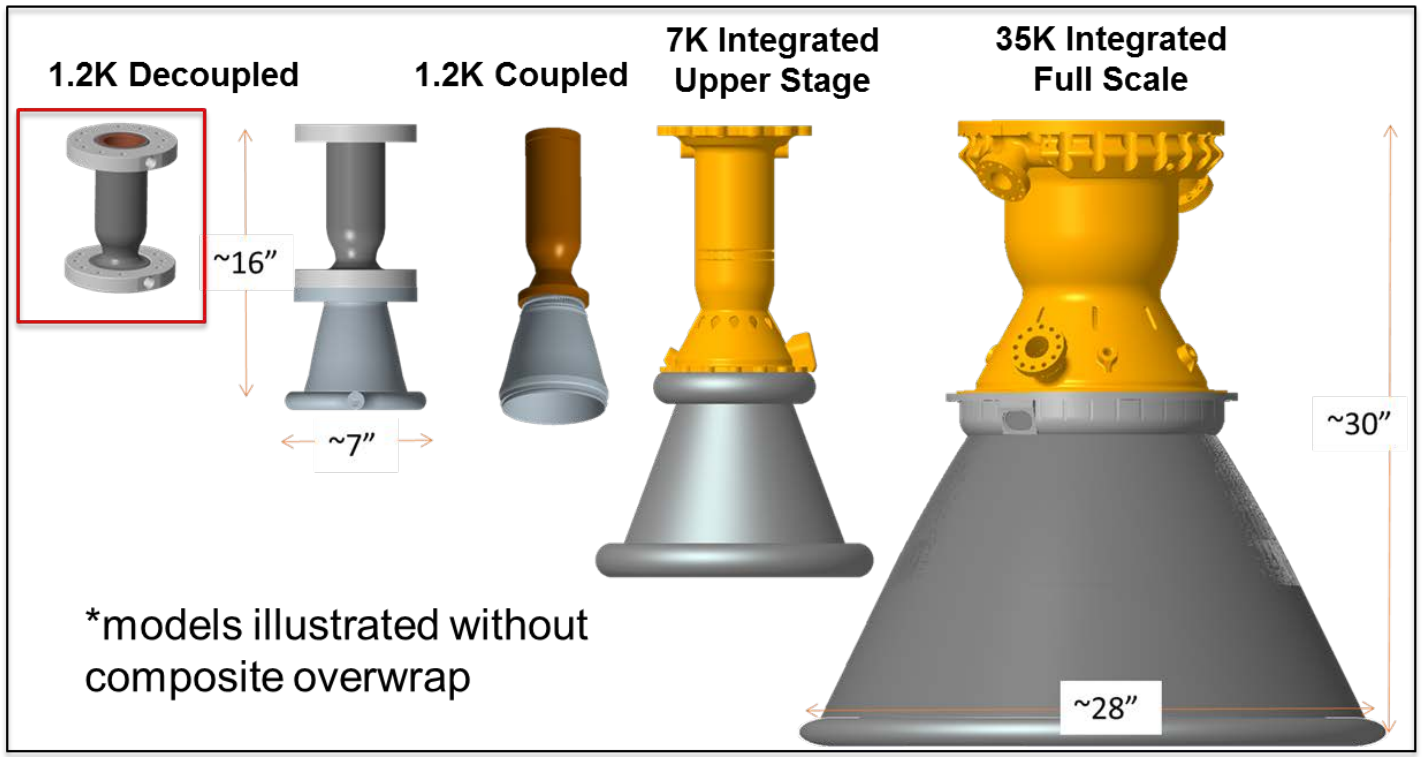
Propulsion systems account for 70% of total vehicle cost and the thrust chamber assembly (TCA) accounts for 50% of cost and >50% of weight

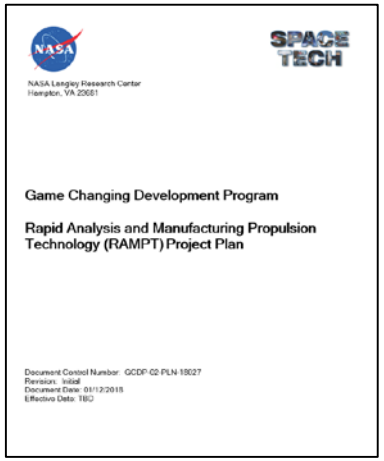


Addresses longest lead, highest cost and heaviest component in engine

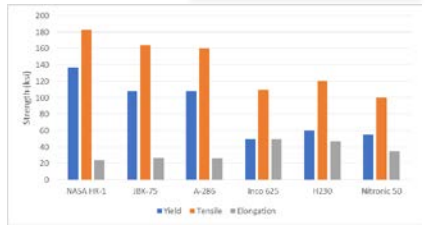
Completed Major Trades for Hardware Development Plans

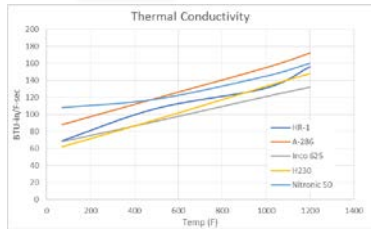
- ✓ Completed detail project plan
- ✓ Completed detailed Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL) assessments using new STMD ranking process
- ✓ Completed detailed risks evaluations for each process operation
- ✓ Completed plans for development and hot-fire testing hardware and conceptual designs
- ✓ Completed material trades for nozzle fabrication and bimetallic joints





	NASA HR-1	JBK-75	A-286	Inco 625	H230	Nitronic 50
Yield (ksi)	137	108	108	50	60	55
Ultimate (ksi)	183	164	160	110	121	100
Elongation (%)	24	27	26	50	47	35
Conductivity, 70F	69		88	68	62	108
Conductivity, 500F	107		119	92	94	118
Conductivity, 1000F	131		155	121	133	145
Conductivity, 1200F	156		172	132	148	160
Density (lb/in3)	0.292		0.286	0.305	0.324	0.285
Modulus (10^6 psi)	29.5		29.1	29.4	30.3	28.9

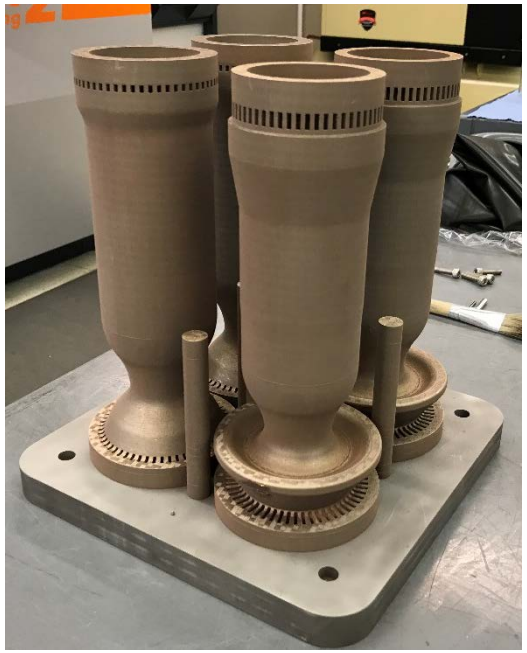




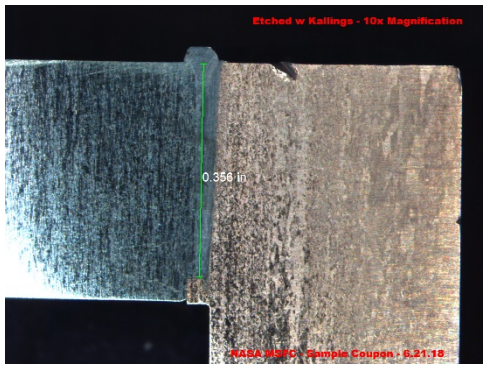
Design and Development of Pathfinder Hardware

Completed additive manufacturing of GRCop-84 pathfinder chambers at commercial vendor, ASRC, for composite overwrap.

Design



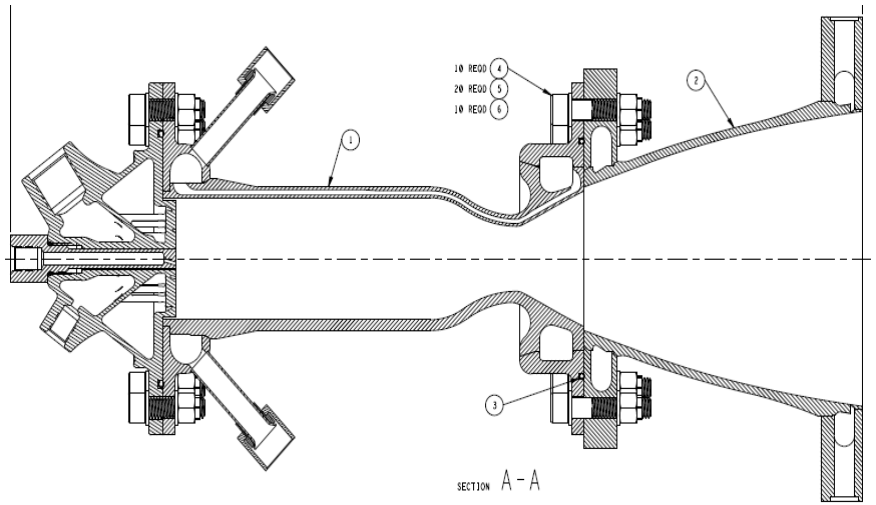
Additive Manufactured GRCop-84 Liners



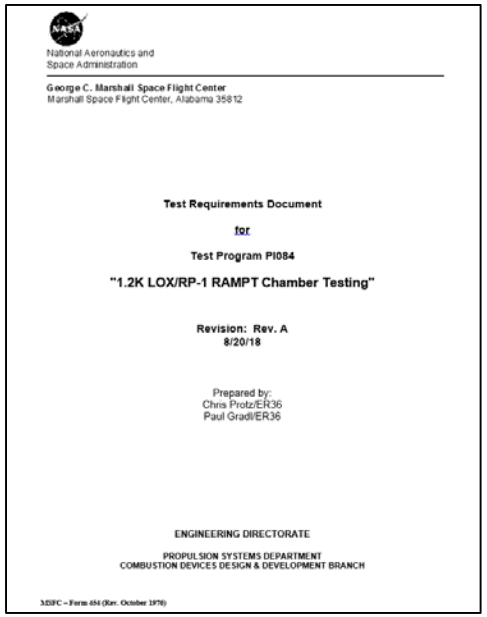
Machined and Dry-fit Manifolds

Setup for Hot-fire Testing of Composite Overwrap GRCop-84 SLM Chambers

- **Completed Test Requirements Document (TRD) Supporting the LOX/Kerosene 1.2K check-out testing on the chambers – setup started**
- **Partnership established with Virgin Orbit as part of RAMPT**
  - Virgin Orbit is committed to match ~40% of funding for hot-fire testing under a Space Act Agreement (SAA) due to shared interest
  - SAA has been approved by MSFC and Virgin Orbit and funding received



NASA MSFC Test Program PI084



National Aeronautics and Space Administration

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Test Requirements Document

for

Test Program PI084

"1.2K LOX/RP-1 RAMPT Chamber Testing"

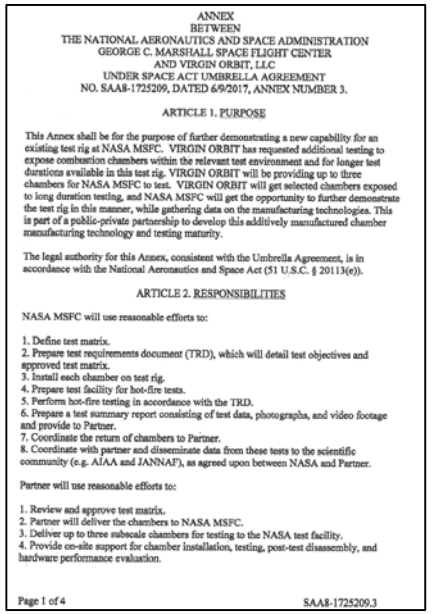
Revision: Rev. A
8/20/18

Prepared by:
Chris Protz/ER36
Paul Gradl/ER36

ENGINEERING DIRECTORATE

PROPULSION SYSTEMS DEPARTMENT
COMBUSTION DEVICES DESIGN & DEVELOPMENT BRANCH

MSFC – Form 454 (Rev. October 1976)



ANNEX
BETWEEN
THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
AND VIRGIN ORBIT, LLC
UNDER SPACE ACT UMBRELLA AGREEMENT
NO. SAA8-1725209, DATED 6/9/2017, ANNEX NUMBER 3.

ARTICLE 1. PURPOSE

This Annex shall be for the purpose of further demonstrating a new capability for an existing test rig at NASA MSFC. VIRGIN ORBIT has requested additional testing to expose combustion chambers within the relevant test environment and for longer test durations available in this test rig. VIRGIN ORBIT will be providing up to three chambers for NASA MSFC to test. VIRGIN ORBIT will get selected chambers exposed to long duration testing, and NASA MSFC will get the opportunity to further demonstrate the test rig in this manner, while gathering data on the manufacturing technologies. This is part of a public-private partnership to develop this additively manufactured chamber manufacturing technology and testing maturity.

The legal authority for this Annex, consistent with the Umbrella Agreement, is in accordance with the National Aeronautics and Space Act (51 U.S.C. § 20113(e)).

ARTICLE 2. RESPONSIBILITIES

NASA MSFC will use reasonable efforts to:

1. Define test matrix.
2. Prepare test requirements document (TRD), which will detail test objectives and approved test matrix.
3. Install each chamber on test rig.
4. Prepare test facility for hot-fire tests.
5. Perform hot-fire testing in accordance with the TRD.
6. Prepare a test summary report consisting of test data, photographs, and video footage and provide to Partner.
7. Coordinate the return of chambers to Partner.
8. Coordinate with partner and disseminate data from these tests to the scientific community (e.g. AIAA and JANNAF), as agreed upon between NASA and Partner.

Partner will use reasonable efforts to:

1. Review and approve test matrix.
2. Partner will deliver the chambers to NASA MSFC.
3. Deliver up to three subscale chambers for testing to the NASA test facility.
4. Provide on-site support for chamber installation, testing, post-test disassembly, and hardware performance evaluation.

Page 1 of 4 SAA8-1725209.3

SAA8-1725209, Annex 3

Technical Status

- All looked great for the injector to be used for RAMPT PI084 testing.

- Some residual powder that was removed with acetone, soaked over the weekend. All LOX and fuel holes flowed good and impingement angles/point as expected.

Procurement Status

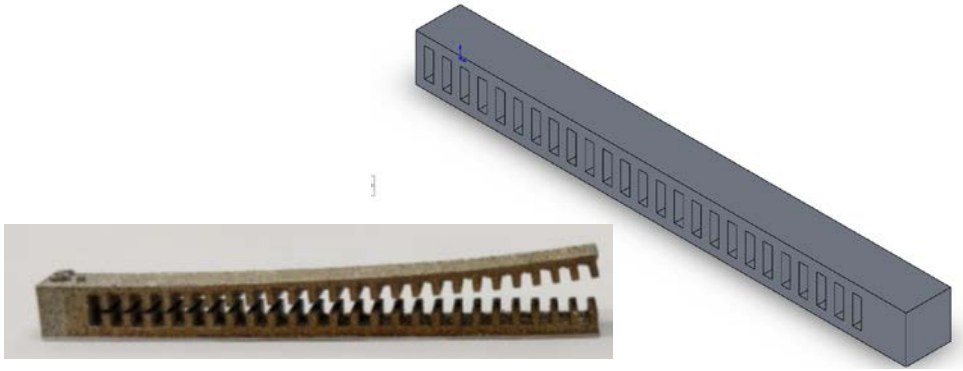
- **Throughout FY18, a series of procurement strategies were proposed and reviewed and finally settled on a sole-source with Auburn University based on existing MSFC Cooperative Agreement Notice (CAN) for establishing public private partnerships**
  - Reviewed by MSFC procurement and legal
  - Completed notice of intent solicitation notice and posted to Fedbiz Ops; no comments provided in return
  - Statement of work and detailed estimates currently in review

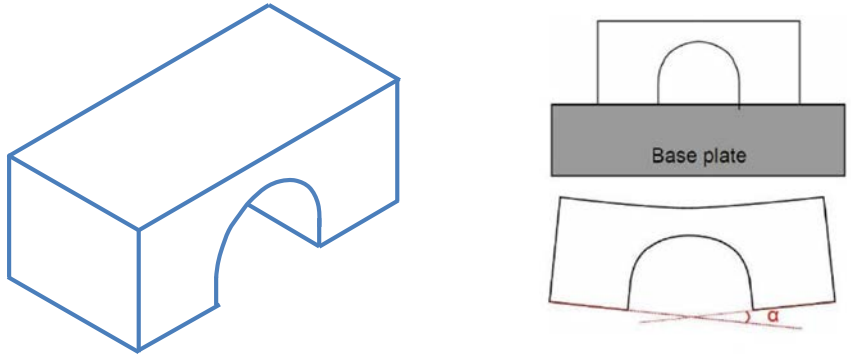
- **SOW includes establishing public-private partnerships (PPP) for the (3) key technology areas under RAMPT in addition to material characterization through Auburn Additive Center of Excellence**
  - Provides NASA access to additional partners including NIST

Technical Status

➢ FY18 Milestones Completed

- Milestone complete: “Develop Additive Modeling Requirements and Plan”, 7-18, ARC, LaRC.
  - Living document developed that defines the requirements and plan for additive modeling task. Validation plan and modelling approach specified.





Coupons designed to validate residual stress (RS) predictions.

Top: Alligator coupon, Bottom: Arch coupon.

Both designs have been successfully used in the past by NASA to study RS in additive manufacturing

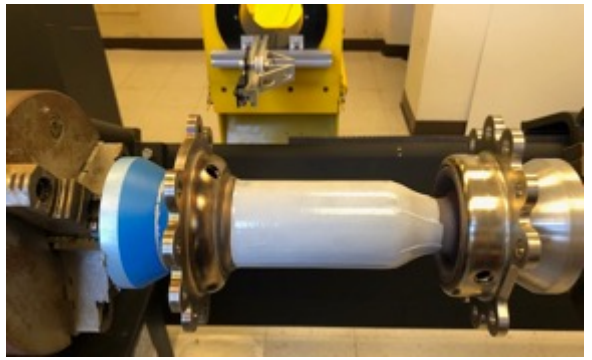
Rapid Analysis and Manufacturing Propulsion Technology (RAMPT)
Initial Trial of Composite Overwrapped 1.2K GRCop Chamber
API Milestone Completion

Objective: Process development for manufacture of composite overwrap on a metallic thrust chamber.

Date	
Scheduled	8/31/2018
Actual	8/31/2018

Key Accomplishment: Developed the manufacturing process for a composite overwrapped structural jacket on a GRCop 1.2K thrust chamber liner. This included GRC, LaRC and MSFC evaluating different techniques and manufacturing options. An evaluation was made of the fiber angles achievable given the constraints of the part and the winder. A fiber orientation of +/- 40º from the vertical axis of the chamber was achieved. Three resins were evaluated, two toughened epoxies and one toughened bismaleimide; which has a higher temperature capability. 12K and 6K tow variants of IM7 fiber were evaluated. Copper/PMC overwrapped coupons were thermally cycled to evaluate adhesion of the composite to the metallic substrate.

Technology Advancement: The manufacturing process development will be validated at the 1.2K thrust level with a hot fire test in October 2018. This will advance the TRL for this scale to a TRL 4.



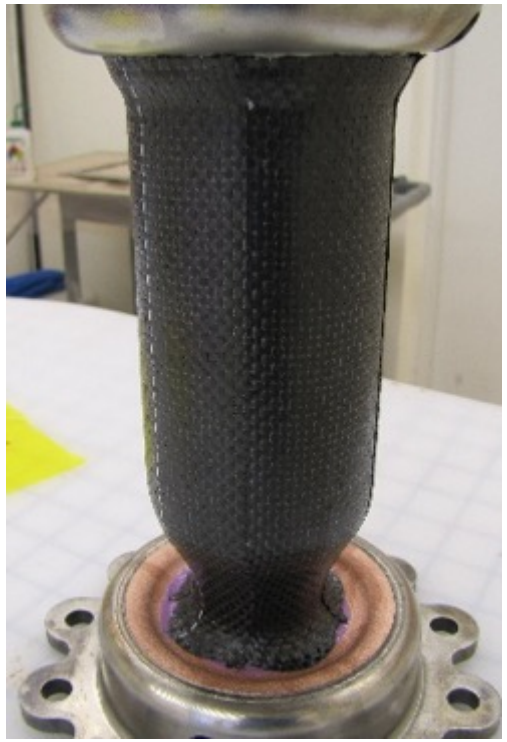
Top Left: Film Adhesive bonded to chamber.

Top Right: Uni-directional tape placed over adhesive.

Bottom: Angle plies and hoop wind with resin application.

Rapid Analysis and Manufacturing Propulsion Technology (RAMPT)
Initial Trial of Composite Overwrapped 1.2K GRCop Chamber (cont.)
API Milestone Completion

- Evaluated adhesive and fabric prepreg overwrap of complex geometry.
- Quasi-isotropic 4 ply layup for MDA.
- Developed template(s) for a consistent overlap of adjacent plies.
- Evaluated multiple bagging schemes on copper (and preceding aluminum) chambers for reduction of defects (wrinkles) in final cured part.
- Investigated surface preparation with initial procedure determined for MDA.



Plain weave fabric overwrap of chamber and adhesive.

Surface prep of copper chamber (grit blast and AC-130-2 surface pre-treatment).

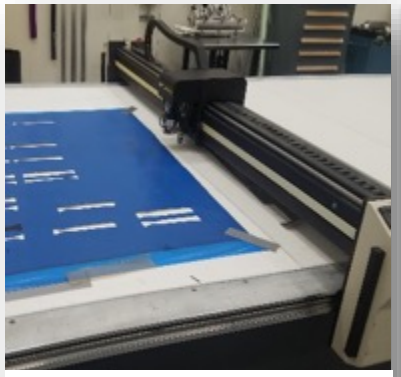
Template for ply 1 (Separate templates for adhesive and each ply accounting for thickness of material).

Vacuum bag setup prior to cure.

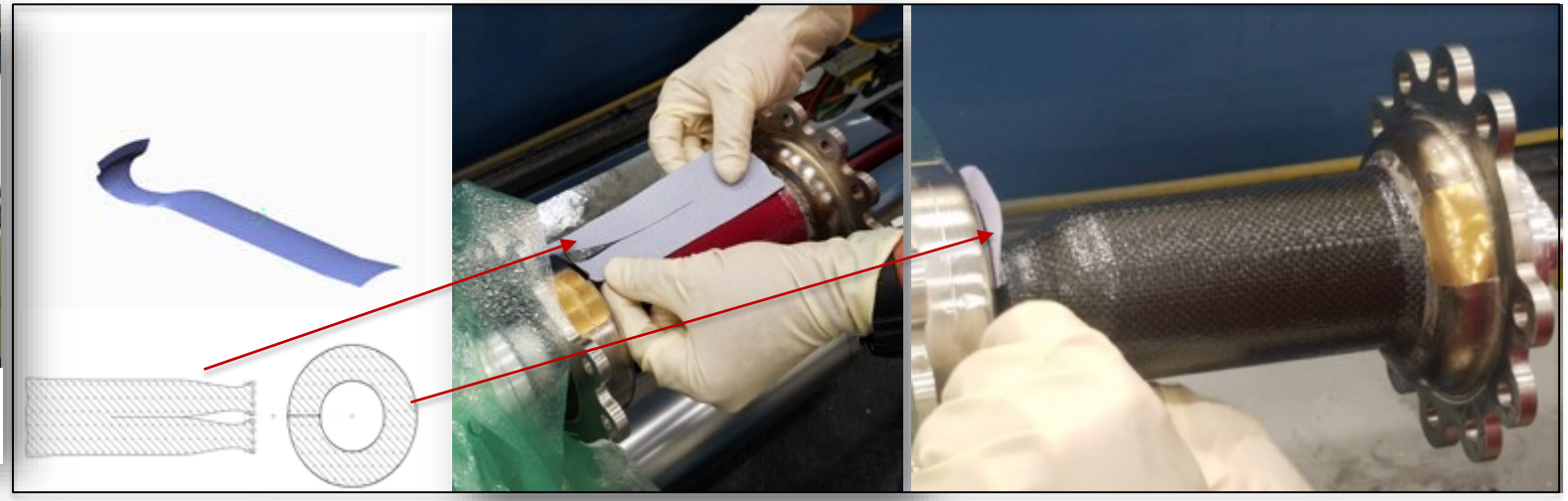
Rapid Analysis and Manufacturing Propulsion Technology (RAMPT)
Initial Trial of Composite Overwrapped 1.2K GRCop Chamber (cont.)
API Milestone Completion

Creation of Preforms:

- ✓ 45 arc section surface extracted from the 3D CAD.
- ✓ Pattern flattened into 2D CAD file.
- ✓ Hand layup of digitally cut pattern onto part.



Digital Cutting of Fabric Preforms for Hand Layup



The Thermal Quench:

- ✓ Immersion in LN_2 (-196° C)
- ✓ No visible delamination

After immersion in LN_2

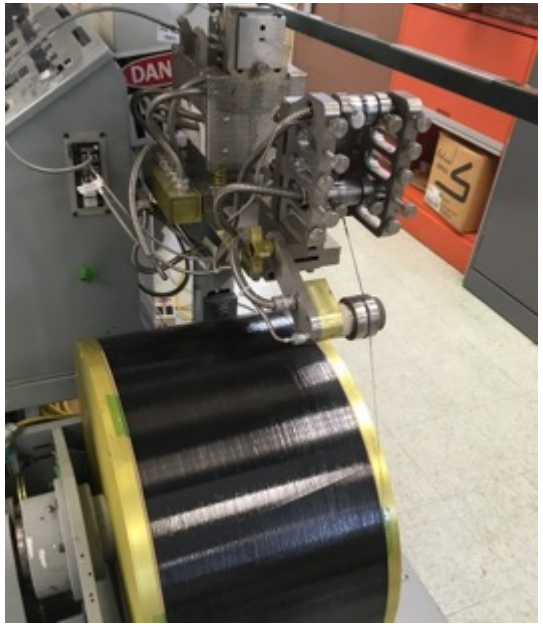
Part at Room Temperature After Quench

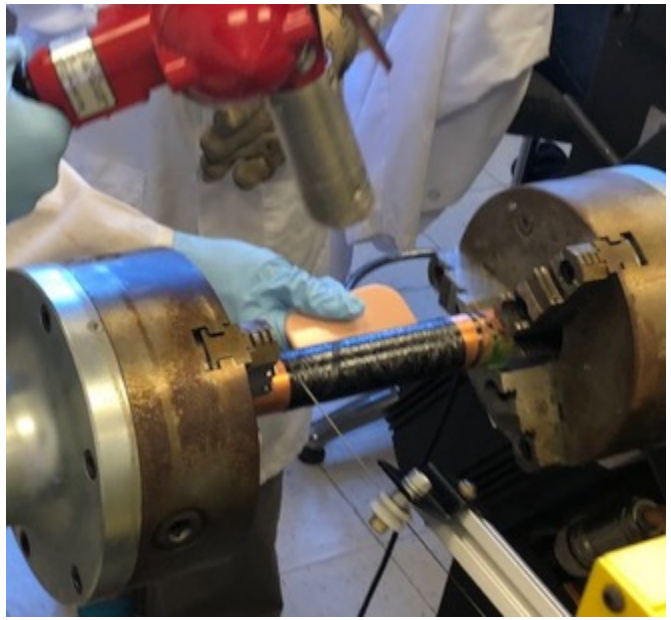
Rapid Analysis and Manufacturing Propulsion Technology (RAMPT)
Initial Trial of Composite Overwrapped 1.2K GRCop Chamber (cont.)
API Milestone Completion

PMC Overwrap: Evaluated two ply configurations on copper for thermal cycling.
±40, 90, ± 40, 90
0, ±40, 90, ± 40, 90

Prepared coupons with and without film adhesive.

Unidirectional layers were prepared in-house using a hot-melt prepregger.



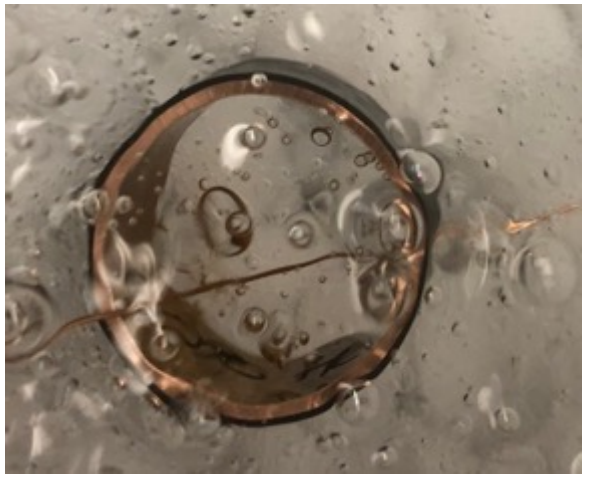


Fiber winding with the BMI required heat application throughout the process.

The thermal cycle used on the overwrap coupons followed:

-100°F, hold 10 min
+400°F hold 10 min

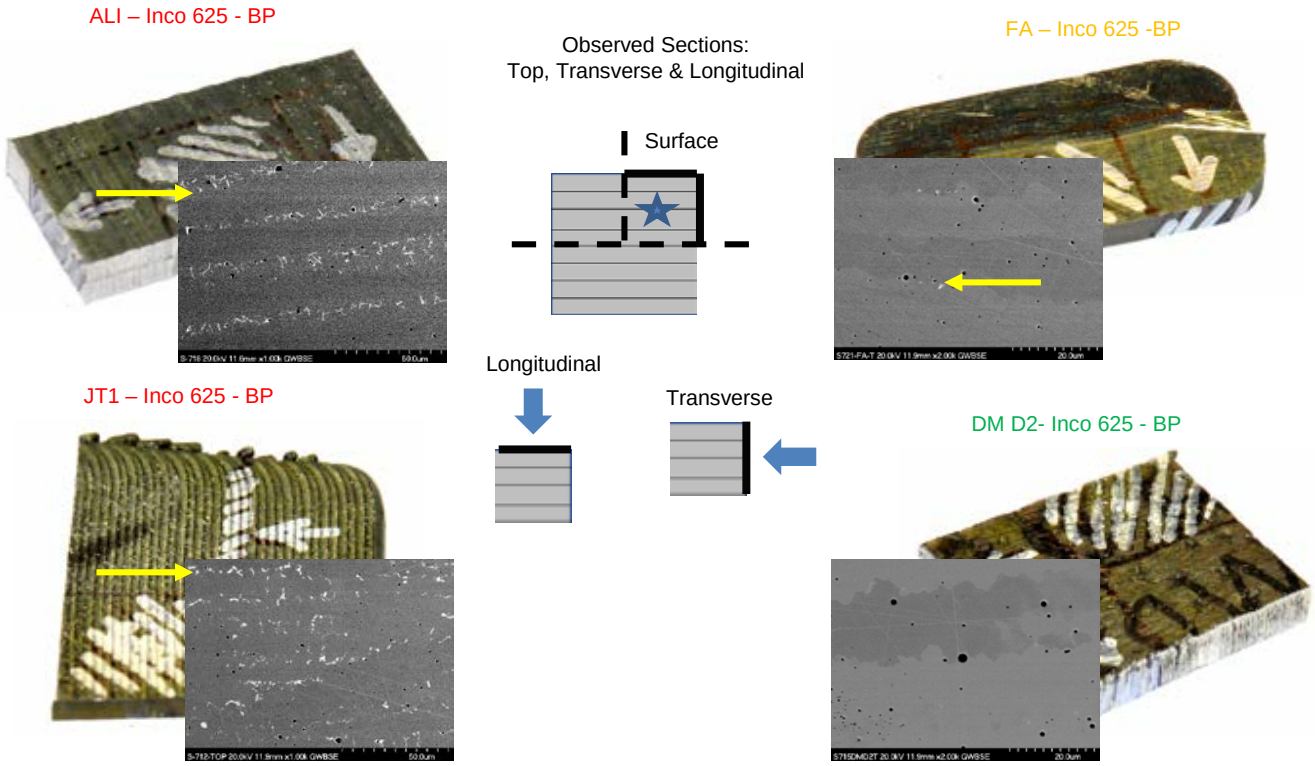
10 cycles.



Without film adhesive, the overwrap separated from the copper after 1-4 cycles.

Technical Status

- Materials
  - Blown powder vendor evaluation
    - Small disks of blown powder IN625 from Formalloy (FA), Alabama Laser (AL), Joining Tech (JT1), DM3D (stress relief 1650F for 1.5 hrs) were evaluated. Macro imaging complete, polished cross-section optical and SEM complete, quantitative wet chemical analysis completed and reported.



Figures: Small disks of blown powder IN625 from various vendors for analysis. High nitrogen (N) content in AL and JT samples, along with aligned secondary Laves phases (white phase in images) throughout discourage further purchase. The Laves phase is undesirable in Inconel alloys as it is detrimental to mechanical properties and it can not be dissolved when joined to GRCop. The FA sample showed limited presence of the Laves phase. The DM3D sample did not exhibit any Laves phase or N, and of the four is our recommended vendor based on provided samples.

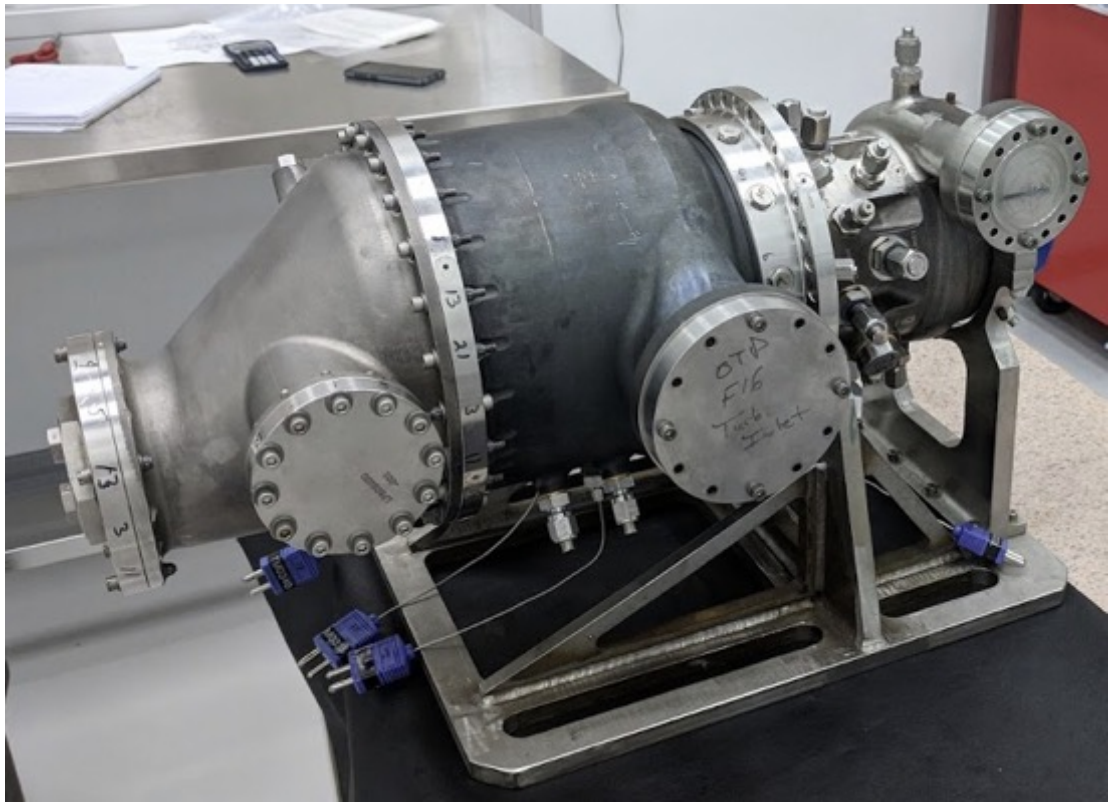
AMT Turbomachinery: Testing Complete API Milestone Completion

Objective: Demonstrate additively manufactured rotating, vane, and critical pressure vessel components in relevant oxygen turbopump environments.

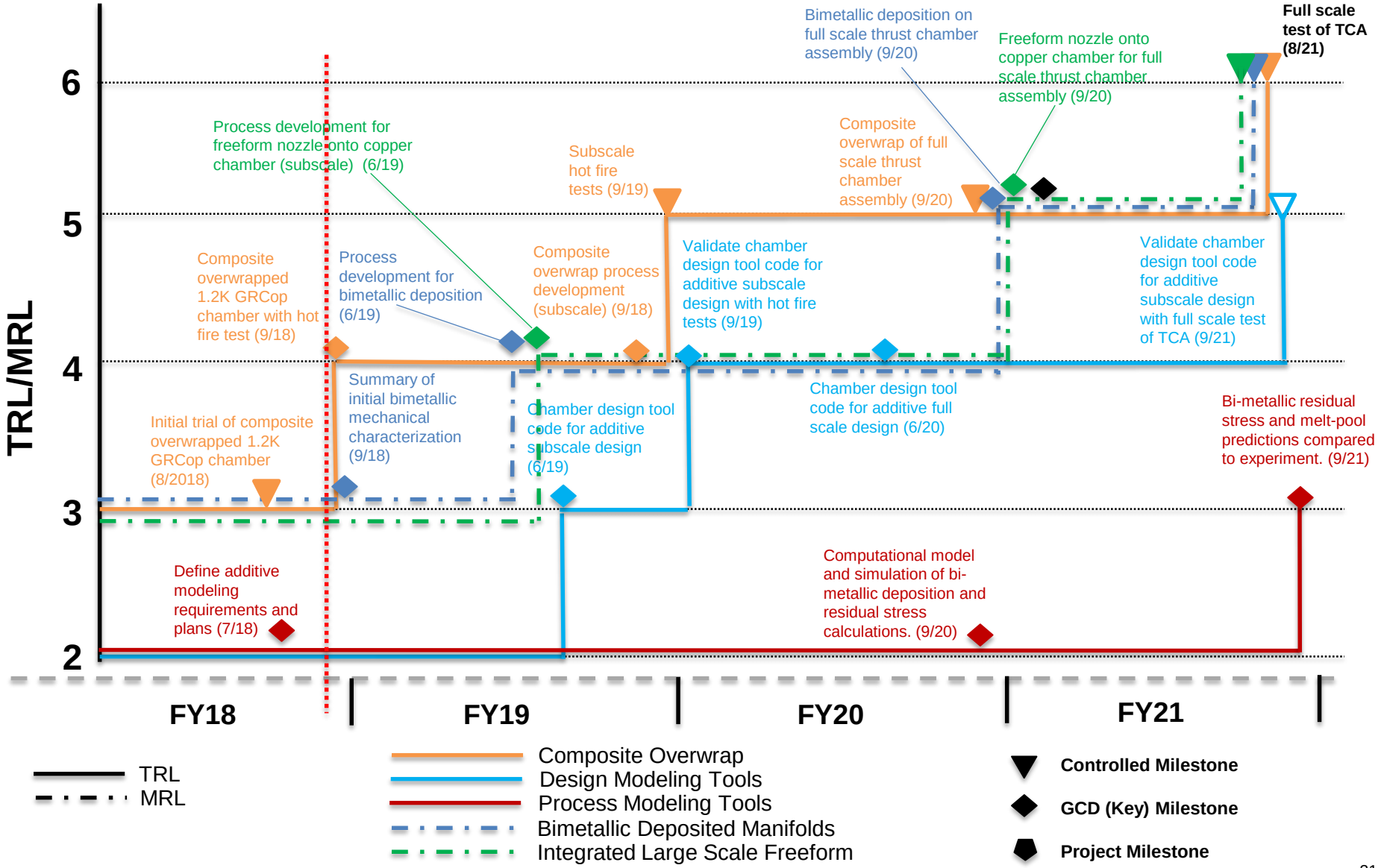
Schedule Completion	
Scheduled	5/23/18
Actual	8/22/18

Key Accomplishment: Successfully additively manufactured, assembled and tested LOX turbopump hardware in a relevant liquid oxygen turbopump environment.

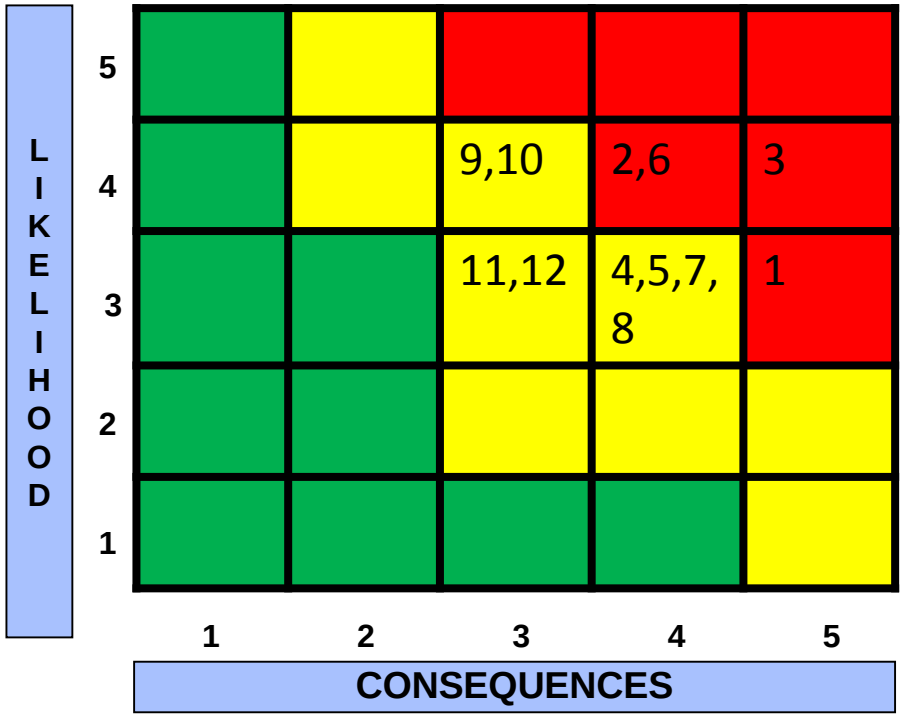
Significance: Infusing additive manufacturing into the design process for oxidizer turbomachinery promises to drastically reduce development costs and lead times for the government and it industry partners. Successfully testing this hardware demonstrates that the technology is viable for these extreme environments and conditions.



RAMPT
IMS/TRL Alignment



Risk Summary



Criticality
- High
- Med
- Low

L x C Trend
- Decreasing (Improving)
- Increasing (Worsening)
- Unchanged
- New Since Last Period

Approach
- M - Mitigate
- W - Watch
- A - Accept
- R - Research

Affinity: **T**-Technical **C**-Cost **Sc**-Schedule **Sa**-Safety

Risk ID	Affinity	Description/Status	Trend
1	M/T,Sc	Localized high residual stresses in bimetallic joints	⇨
2	M/T,P	Nozzle geometries cause localized high temperature regions	⇨
3	M/T,P	Polymer Matrix Composites Not Suitable for Application	⇨
4	M/Sc	Limited production capacity of GRCop-84 chambers	⇨
5	M/Sc	Limited Production Capacity of New Technologies	⇨
6	M/T,C,Sc	Failures during large scale freeform deposition	⇨
7	M/C,Sc	Powder removal difficult in parts with small channels	⇨
8	W/C,Sc,P	Full scale chamber/nozzle availability for integration	⇨
9	W/Sc	Modeling Requires Empirical Data from Newly Fabricated Hardware	⇨
10	W/Sc	Design Suite Requires Empirical Data from Newly Fabricated Hardware	⇨
11	W/Sc	Manufacturing or Testing Availability	⇨
12	W/Sc	Test Stand Conflicts	⇨

EPO Summary Chart

➢ Summary of Education and Public Outreach

- JANNAF: Joint Army-Navy-NASA-Air Force (Long Beach, CA) – May 21-24, 2018
- 54th AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum (Cincinnati, OH) – July 9-12, 2018
- JANNAF: Joint Army-Navy-NASA-Air Force (Huntsville, AL) – August 27-28, 2018

Annual Summary

- RAMPT project is developing a sole-source contract with Auburn University based on existing MSFC Cooperative Agreement Notice (CAN) for establishing public private partnerships.
  - Statement of work and detailed estimates currently in review
  - Plan is to have contract in place to start FY19.

- Completed detail project plan and detailed Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL) assessments using new STMD ranking process.

- Completed additive manufacturing of GRCop-84 pathfinder chambers at commercial vendor, ASRC, for composite overwrap.

- Completed “Initial Trial of Composite Overwrapped 1.2K GRCop Chamber” RAMPT API Milestone.

- Completed the AMT Turbomachinery API Milestone “Testing Complete”

- Completed Test Requirements Document (TRD) Supporting the LOX/Kerosene 1.2K check-out testing on the chambers – setup started
  - Virgin Orbit is committed to match ~40% of funding for hot-fire testing under a Space Act Agreement (SAA) due to shared interest


BACKUP

Annual Assessment Summary

Technology	Mid Year				Annual Performance				Comments
	C	S	T	P	C	S	T	P	
TRL Element #1 Composite Overwrap									➢ Completed “Initial Trial of Composite Overwrapped 1.2K GRCop Chamber” RAMPT API Milestone.
TRL Element #2 Design Modeling Tools									
TRL Element #3 Process Modeling Tools									➢ Completed “Develop Additive Modeling Requirements and Plan” milestone.
MRL Element #1 Bimetallic Deposited Manifolds									
MRL Element #2 Integrated Large Scale Freeform									

EPO Summary Chart

➢ Conferences attended

Conference Name	Papers/Posters/Panel Discussions
Example: AIAA Space	Quote Paper/Poster/Panel Here
JANNAF: Joint Army-Navy-NASA-Air Force (Long Beach, CA)	2 Papers
JANNAF: Joint Army-Navy-NASA-Air Force (Huntsville, AL)	2 Papers, 1 Poster
54th AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum	1 Paper, 1 Panel Discussion

➢ Academic involvement

# of Students	Education Level	School Name
1	Senior	Case Western Reserve University

GCD Project Performance Evaluation Criteria

	Technical/Performance
Green	Project is demonstrably making progress on the Learning Trajectory (e.g. milestones met, knowledge advanced) or advancing TRL. Project is on track to meet L1 requirements.
Yellow	Project is making progress on the Learning Trajectory or advancing TRL with issues. Project is on track to meet L1 requirements but issues exist that may threaten achievement.
Red	Project has ceased to make progress on the Learning Trajectory or advance TRL. Project is unable to meet one or more L1 requirements.

	Cost
Green	Project can meet its commitments with its planned/allocated budget.
Yellow	Project cannot meet its commitments within its planned/allocated budget but will not be requesting additional budget from Program. Mitigation plans have been developed.
Red	Project cannot meet its commitments within its planned/allocated budget and will be requesting additional budget from Program.

	Schedule
Green	Project can meet its commitments within its planned/allocated schedule baseline for critical milestones.
Yellow	Project cannot meet its commitments within its planned/allocated schedule baseline but mitigation plans have been developed to pull it back in.
Red	Project cannot meet its commitments within its planned/allocated schedule baseline.

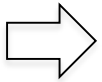
	Programmatic (Institutional, Internal/External Dependencies **)
Green	Relevance of technology to stakeholders and/or technology infusion path is maintained. Mission sponsor still actively interested. No issues exist with workforce, test facilities, etc.
Yellow	Relevance of technology to stakeholders and/or technology infusion path are threatened. Mission sponsor backing off. Issues exist with workforce, test facilities, etc. but plans to mitigate are available.
Red	Relevance of technology to stakeholders and/or technology infusion path are not projected to be met, or has lost relevance to stakeholders. Mission sponsor cancelled interest. Issues pertaining to workforce, test facilities, etc. are preventing progress along the Learning Trajectory.

Source: BPR Assessment Criteria for NASA R&T Projects, OCE/S. Hirshorn, 09/17/2015

1. Localized high residual stresses in bimetallic joints (Carter)

1

Trend



Criticality

H

Current LxC
3x5

Affinity Group
T/Sc

Planned Closure
TBD

Open Date
5/17/18

- Risk Statement: Given that joints between dissimilar metals are subject to cracking due to deposition technique/heat load/CTE mismatch/differential cooling/solidification rates and due to specific geometries that create localized high residual stresses, there is a possibility that fabrication technique-induced cracking will limit the achievable bond strength, thereby causing a risk to meeting the KPP of testing bimetallic joints at thrust classes.
- Approach: Mitigate
- Context: EBF^3 direct bimetallic deposition was performed successfully on LCUSP, allowing high stress fuel blowdowns and hot fire tests on a full scale test article. Work with direct bimetallic deposition, including in the LCUSP project, has shown the potential for forming localized hot-cracking and high residual stresses, and these results are also geometry dependent. Work in RAMPT will further mitigate these side effects.
- Status: Initial Risk Statement

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
1. Evaluating metallurgical causes for cracking observed in recent bimetallic work in order to determine alternate jacket alloys or to eliminate the formation of secondary phases that can lead to cracking.					3x5
2. Phase 1 of solicitation includes requirements for samples. GRC to characterize and evaluate for phase 2 awards					3x5
3. Geometry trials with geometries representative of test article geometries.					2x5
4. Perform deposition on specimens with high fidelity test article geometries before proceeding to test article.					1x5

2. Nozzle geometries cause localized high temperature regions (Protz)

2

Trend

Criticality

H

Current LxC
4x4

Affinity Group
T/P

Planned Closure
TBD

Open Date
5/17/18

- Risk Statement: Given that multi-material interfaces require width for the interfaces to be completed, there is a risk that these fabrication constraints will cause designs to exceed the maximum distances from coolant to the hot wall in low conductivity nozzle materials, thereby causing localized hot streaks on the nozzle that could lead to overheating and erosion/low strength regions.
- Approach: Mitigate
- Context: Multi-material interfaces are an innovative technology being developed under RAMPT, and the limit of distance to complete the interface is currently unknown. Cooled nozzles require coolant near the surface to be cooled, and the design requirements and fabrication limits will be evaluated in RAMPT.
- Status: Initial Risk Statement

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
1. Design and analysis to be preformed to create designs that push limits of existing weld technology.					4x4
2. Alternate vendors may be considered, pending results of initial trials by primary vendor.					3x4
3. Deposition trials will be performed on multiple geometries to down select geometries.					2x4
4. Early hot fire tests will be overcooled to evaluate design margin relativize to models					2x3

3. Polymer Matrix Composites Not Suitable for Application (Jackson)

3

Trend

⇨

Criticality

H

Current LxC
4x5

Affinity Group
T/P

Planned Closure
TBD

Open Date
5/17/18

- Risk Statement: Given the extreme environments experienced by the chamber, a suitable fiber-reinforced polymeric material may not adequately transfer the necessary loads. (i.e. properties degrade over the temp/load range).
- Approach: Mitigate
- Context: Composite materials will have a significant CTE mismatch vs the metallic substrate, the degradation of bond line due to thermal cycling from -300F for cryogenic fuels or ambient for kerosene to 500F under hot fire conditions could initiate cracking and thus the loss of load transfer.
- Status: Initial Risk Statement

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
1. Perform robust material survey and substantiate with coupon level testing to demonstrate adequate materials and processes.					4x5
2. Vendors submitting to the RFQ will be rated on their plans for addressing this risk area.					3x5
3. Initial 1.2k tests conducted with kerosene.					2x5
4. In-house material survey and coupon level testing results will be transferred to industry/RFQ awardees.					2x5

4. Limited production capacity of GRCop-84 chambers (GradI)

4

Trend

⇨

Criticality

M

Current LxC
3x4

Affinity Group
Sc

Planned Closure
TBD

Open Date
5/17/18

- Risk Statement: Given that there is currently limited production capacity of GRCop-84 chambers, there is a risk of schedule delays in getting all substrate parts for RAMPT technologies made, thereby leading to delays in meeting scheduled milestones.
- Approach: Mitigate
- Context: SLM GRCop-84 manufacturing was developed and transitioned to industry under the LCSUP project, but the current demand from commercial and government entities exceeds the production capacity.
- Status: Initial Risk Statement

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
1. Allow for margin to delivery schedule					2x4
2. Ensure funds are available on time to commit to commercial vendors to secure our positions in the queue					2x4
3. Work closely with Commercial SLM vendors to ensure our parts are scheduled					1x4
4.					

5. Limited Production Capacity of New Technologies (Protz/Gradl)

5

Trend

⇨

Criticality

M

Current LxC
3x4

Affinity Group
Sc

Planned Closure
TBD

Open Date
5/17/18

- Risk Statement: Given that large scale Freeform Nozzle and Composite Overwrap TCA demonstrator parts have more complex manufacturing flows and more complexity in process development than initial small scale units and given that production volume is limited for these new technologies, there is a risk that production of these parts will encounter unforeseen delays, thereby causing delivery schedule delays that can impact milestone dates.
- Approach: Mitigate/Accept/Watch
- Context: As part sizes increase, fabrication time, shipping complexity, and shop floor maneuvering increase.
- Status: Initial Risk Statement

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
1. Allow for margin to delivery schedule					2x4
2. Ensure funds are available on time to commit to commercial vendors to secure our positions in the queue					2x4
3. Work closely with Commercial SLM vendors to ensure our parts are scheduled					1x4
4.					

6. Failures during large scale freeform deposition (Protz/Gradl)

6

Trend

⇨

Criticality

H

Current LxC
4x4

Affinity Group
T/C/Sc

Planned Closure
TBD

Open Date
5/17/18

- Risk Statement: Given that RAMPT will develop fabrication technologies and ramp up the size of articles produced over time, there is a possibility that new failures will be encountered during large scale freeform deposition, that were not observed in smaller scale development, thereby causing schedule delays as failures are investigated and recovery plans undertaken.
- Approach: Mitigate (limited)
- Context: Recent experience shows that as advanced manufacturing technologies have been scaled up, there is a potential for new challenges to be discovered.
- Status: Initial Risk Statement

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
1. Include schedule margin for failed build based on past experience.					4x4
2. : Include designs and schedule for trial builds of small wedges before full builds to test buildability and larger geometries.					3x4
3.					
4.					

7. Powder removal difficult in parts with small channels (Protz/Gradl)

7

Trend

⇨

Criticality

M

Current LxC
3x4

Affinity Group
C/Sc

Planned Closure
TBD

Open Date
5/17/18

- Risk Statement: Given that powder removal has been an issue for parts with small (<0.080”) channels there is a possibility that CT inspections will reveal blocked passages, thereby causing schedule delays as the powder will have to be removed via additional conventional methods or via unconventional methods.
- Approach: Mitigate
- Context: Recently fabricated parts have shown difficulties removing powder. The primary successful mitigation has been designing for individualized powder removal access to channels.
- Status: Initial Risk Statement

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
1. Parts fabricated with powders will be CT inspected before further processing steps					3x3
2. Design panels to allow for individualized powder removal.					2x2
3. Mitigation Option: Pursue innovative powder removal techniques such as resonant vibrations					1x2
4. Mitigation Option: Design for invasive powder removal techniques as a final option that could be weld repaired costing schedule if that option costs less schedule than remanufacturing the entire part.					1x2

8. Full scale chamber/nozzle availability for integration (Protz/Gradl)

8

Trend

⇨

Criticality

M

Current LxC
3x4

Affinity Group
C/Sc/P

Planned Closure
TBD

Open Date
5/17/18

- Risk Statement: Given that multiple innovative technologies are being developed under RAMPT and the end goal is to integrate them into one unit in year 3, there is a possibility that one technology will suffer delays thereby causing schedule delays on the delivery of the integrated unit.
- Approach: Watch
- Context: Delivery of a final integrated part requires at least threshold capabilities for each technology.
- Status: Initial Risk Statement

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
1. Conduct periodic evaluation of progress of each technology and readjust resources if needed to accelerate any lagging items.					3x3
2.					
3.					
4.					

9. Modeling Requires Empirical Data from Newly Fabricated Hardware (Protz/Gradl)

9

Trend

⇨

Criticality

M

Current LxC
4x3

Affinity Group
Sc

Planned Closure
TBD

Open Date
5/17/18

- Risk Statement: Given that the AM Modeling requires empirical data from newly fabricated, never before attempted designs, there is a risk of early build failures thereby impacting the modeling effort/schedule
- Approach: Watch
- Context: The ability to analyze fabrication techniques relies on comparing the analysis to empirical data. The fabrication of these designs has not been attempted before and may require development.
- Status: Initial Risk Statement

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
1. Include schedule margin for failed build based on past experience					3x3
2. Include schedule for trial builds of small wedges before full builds to test buildability					2x3
3.					
4.					

10. Design Suite Requires Empirical Data from Newly Fabricated Hardware (Protz/Gradl)

10

Trend

⇨

Criticality

M

Current LxC
4x3

Affinity Group
Sc

Planned Closure
TBD

Open Date
5/17/18

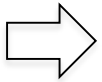
- Risk Statement: Given that the Chamber design suite requires empirical data from newly fabricated, never before attempted designs, there is a risk of early build failures thereby impacting the design tool schedule
- Approach: Watch
- Context: The ability to analyze innovative coolant passage features and designs rely on comparing the analysis to empirical data. The fabrication of these designs has not been attempted before and may require development.
- Status: Initial Risk Statement

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
1. Include schedule margin for failed build based on past experience					3x3
2. Include schedule for trial builds of small wedges before full builds to test buildability					2x3
3.					
4.					

11. Manufacturing or Testing Availability (Protz/Gradl)

11

Trend



Criticality

M

Current LxC
3x3

Affinity Group
T/C/Sc/Sa/P

Planned Closure
TBD

Open Date
5/17/18

- Risk Statement: Given that hot-fire testing is required to provide empirical data to the new models, there is a possibility testing could be delayed by manufacturing or testing availability schedules, thereby impacting the delivery dates of the data and causing the software to be delayed beyond milestone dates
- Approach: Watch
- Context: Test and manufacturing schedules are subject to agency and commercial priorities. Frequent communication ensures opportunities for testing and fabrication are capitalized.
- Status: Initial Risk Statement

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
1. Add margin to design tool delivery schedule.					3x3
2. Work closely with Commercial SLM vendors to ensure our parts are scheduled.					2x3
3. Ensure funds are available on time to commit to test area to secure our positions in the queue.					2x3
4.					

12. Test Stand Conflicts (Protz/Gradl)

12

Trend

Criticality

M

Current LxC
3x3

Affinity Group
T/C/Sc/Sa/P

Planned Closure
TBD

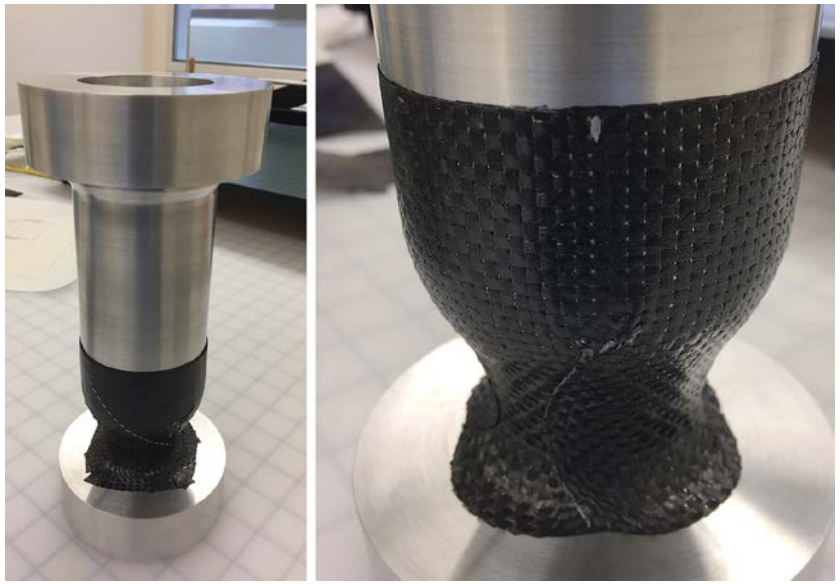
Open Date
5/17/18

- Risk Statement: Given that multiple projects may require capabilities of a single test position, there is a risk that RAMPT testing could be delayed due to test stand conflicts causing milestone slips.
- Approach: Watch
- Context: Test and schedules are subject to agency priorities. Frequent open communication ensures opportunities for testing are capitalized.
- Status: Initial Risk Statement

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C
1. Proper test coordination and scheduling with the test area and teams with potentially conflicting tests.					1x2
2.					1x2
3.					1x2
4.					1x2

Misc photos to possibly use

(May 2018)
Dry IM7 fiber woven at a 40° angle from longitudinal axis onto aluminum mandrel for preliminary overwrap tests.
(S. Miller, D. Gorican, P. Heimann)



(July 2018)
MSFC

Misc photos to possibly use